A web portal for automatic performance evaluation of Lagrangian Particle Tracking and Data Assimilation algorithms

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Keywords: LPT processing, PTV processing, data assimilation, automatic evaluation, benchmark databases, web portal

ABSTRACT

We introduce a web portal dedicated to benchmarking Lagrangian Particle Tracking (LPT) and Data Assimilation (DA) processing algorithms. LPT is here understood in a wide sense, as we consider acquisition situations ranging from only two illuminations (i.e. Particle Tracking Velocimetry - PTV) to a large number of images. The website, https://www.onera.fr/flow-benchmarks allows not only to download datasets, but also to upload results and automatically obtain their performance evaluation; in its principle, it is thus similar to a number of already existing benchmark websites in the computer vision community, while none existed so far in the community of optical metrology for fluid mechanics. On the basis of the obtained performance, a user has the choice to publish their results or not on the public page of the dataset. The present work presents the website structure, its rules for participation, and a description of the first dataset available at opening, namely the two-pulse (PTV) case of the First LPT and DA Challenge dataset (Sciacchitano et al. 2021). The portal is of course to be supplemented with further cases regularly, which can also arise from external contributions, by contacting the development team by email at flow-benchmarks@onera.fr.

1. Introduction

In the last decade, velocimetry approaches based on tracking the motion of individual particles have received considerable interest and achieved substantial progress, owing to their now acknowledged high accuracy in the measurement of volumetric flows (see, e.g. Schanz et al. 2016). Owing to a large proportion of common algorithmic principles, the processing methods, whether considering a small number of images (e.g. 2 in the context of Particle Tracking Velocimetry, PTV) or a large sequence (e.g. 50 to 100 instants) are nowadays commonly referred to as Lagrangian Particle Tracking (LPT).

Due to the scattered nature of the obtained result, at the particles positions only, significant research efforts have also been directed towards the development of related Data Assimilation (DA) techniques, aiming at finally reconstructing full 3D velocity (and possibly pressure) fields on regular Cartesian grids (see, e.g., Schneiders et al. 2016).
Similar to the development of planar or volumetric Particle Image Velocimetry (PIV) processing algorithms, implementing a new code adapted to LPT or DA data mandatorily requires evaluating its performance on synthetic data, which allows comparing against the ground truth and building quantitative error metrics. To help understand the respective behaviour and performances of the various approaches available, the PIV community has quickly adopted the tradition of regularly organizing "challenges", in which synthetic and experimental datasets were made available to teams willing to participate. Organization relied on a defined schedule, with a deadline for result submission, and presentation of the results within a conference or during a dedicated workshop, followed by a journal publication. Following first challenges either on planar PIV (Stanislas et al. 2003, 2005, 2008) or both on planar and on volumetric PIV (Kähler et al. 2016), a specific challenge on LPT and DA was recently organized in the same spirit (Leclaire et al. 2021, Sciacchitano et al. 2021a, 2021b).
While such events are successful in triggering intense developments within the participating teams, and in fostering scientific discussions during result presentation, their punctual nature in time naturally limits the possible number of participants. Further, frequency of their occurrence is directly and only dependent on the availability of teams willing to organize them. Therefore no regularity is guaranteed, as this organization might represent a heavy task.
In the computer vision community, where similar motion tracking algorithms are developed, tradition has rather adopted the development of websites allowing to download the benchmark datasets, to upload results and to automatically obtain their evaluation and ranking (see, e.g., Butler et al. 2012, Geiger et al. 2012). Due to their permanent availability, and to the relevance of the test cases included, these benchmark websites have attracted a considerable number of contributions, and are now considered as references in the field.
The objective of this work is to introduce and launch one such benchmark web portal, targeted towards the community of optical metrology for fluid mechanics, and more precisely LPT and DA techniques. In this paper, we describe its main features, as well as the general rules for result submission and publication, which will hold for all test cases (section 2). We then exemplify in section 3 the processes for result upload, evaluation and publication, and describe how the published results are presented, using the first available dataset, which is the two-pulse case of the 1st LPT Challenge (Leclaire et al. 2021, Sciacchitano et al. 2021a). Section 4 then introduces

the datasets that are planned to be included next, as the portal is thought to be supplemented with new cases regularly, in order to accompany at best the developments of the community.

2. General presentation and rules

We here describe the current layout and rules of the portal. The layout in particular is not yet in its final version at the time of writing of the paper. Screenshots presented in the figures to follow are thus to be considered as “under construction”. Also, some of the principles described below may change in time, depending on the observed use of the website by the research community. It is thus important to note, in particular, that rules applying for submission of results and publication are that which appear on the website, if they differ from that exposed in the present paper.

2.1. URL address and pages

The portal is accessible at the URL address https://www.onera.fr/flow-benchmarks. As seen in Figure 1, it is composed of general pages providing in particular information about the submission rules and the developing team, as well as one page per available test case (or group of test cases). Each test case page contains a subpage providing the description of the dataset, of the input files (including, if the case arises, files that contain information necessary to camera calibration) and of the requested format expected for the results. This subpage also contains links to dowload the input data, and a link to submit a result. Note in particular that all datasets present on the portal can be downloaded freely, without the need of being logged in.
A second subpage is dedicated to presentation of the published results (see section 3.3 for an example).

2.2. Account creation and contact

Account creation is required for submitting a result (and possibly publish it), as well as receiving by e-mail the regular news about the portal, that will be also gathered at the bottom of the Home page. An account can be readily created by using the "Register" link top right of all pages (as visible in Figure 1), by providing your name, email address, affiliation (institution), and choosing a username. The email address should be the one provided by your institution. Optionally, account information can also include the name of your research group/team in your institution.

This information is requested so that results published on the test pages can be as easily as possible related to a research group. In the same spirit, when submitting a result, we give the possibility to indicate a publication related to the algorithm (see section 2.3).

In the idea of keeping fair and balanced performance charts, it was also decided to not allow registering several times with different email accounts.

The contact address of the portal is flow-benchmarks@onera.fr. It can be used in case of trouble when using the portal, for questions, or for suggesting a new benchmark dataset to be included (see section 4.3).

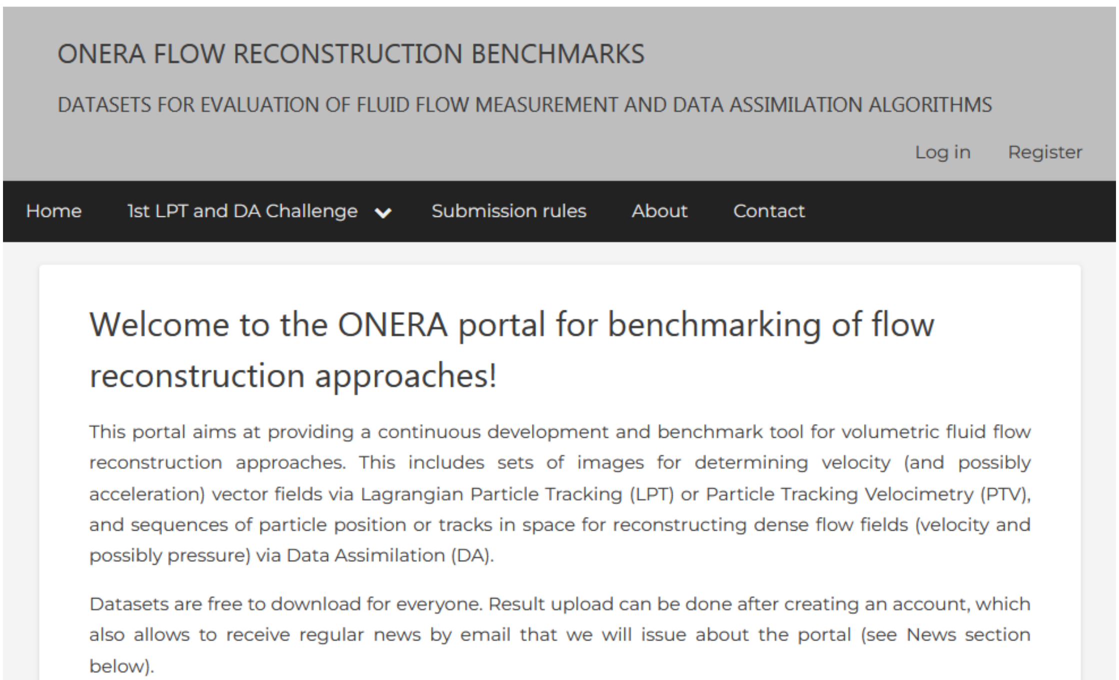


Figure 1 – Partial screenshot of the portal home page (temporary style)

2.3. Submission rules

As a first important remark, it should be mentioned that submitting a result in order to get its performance evaluation does not mean publishing it on the website. As the portal is intended to support continuous development, submission can be performed, and, if judged insufficient, the evaluation can be discarded, possibly leaving the decision of publication to a later and more satisfactory submission.

As mentioned in subsection 2.2, submission of a result first requires to be logged in. Clicking on the "Submit result" button of a test case opens a form, in which the result archive (zip file containing the result files to the test case) can be uploaded. The form should also be completed with information about the algorithm used to produce the results should be indicated, namely:

- The algorithm short name or acronym
- The algorithm full name
- The URL address of a publication or webpage describing the algorithm (optional)

Further information pertaining to result upload may depend on the test case. For an example, see section 3.2.1.

Further to providing the requested information, the following rules apply for result submission:

1. In order to avoid excessive overfitting of methods to the computed performances, the number of submissions per user and per test case is limited to 1 every 15 days, irrespective of publication decision.
2. As long as a user has not decided on accepting or discarding publication of their results, no further result submission is possible to the same data set, even after 15 days. However, the user still has the possibility to upload results to other data sets of the portal (when available).
3. If no decision about publication occurs following 30 days of a result upload, results and performance evaluation will be automatically deleted.

2.4. Publication rules

After result upload, if the archive contains the requested files with correct formatting, evaluation will be performed and, when its computation is finished, the user will receive an email with a link to a form in the portal containing several figures illustrating its performance (see an example in section 3.2.2), and buttons for choosing between publishing or discarding the result.

Publication is subjected to the following rules:

1. A given algorithm may appear only once in the public result tables of a data set. In the case of a new publication of the same algorithm on the data set, results will be replaced.
2. A user may publish the results of up to 5 different algorithms on a given data set.
3. In case several publications have been done with too few differences in the algorithm name (i.e. differences only in parameter setting), you will be asked to indicate the only publication that should be considered in the charts.
4. There is no frequency constraint pertaining to publication for a given data set, other than that linked to submission of results (see the submission rules in section 2.3).

2.5. User data policy

The only user data that is kept on our website is the performance evaluation of a published result. Uploaded results are systematically deleted once the user has completed the evaluation and publication form, irrespective of the decision (Publish or Discard). Also, if the user chooses to discard their evaluation, it will be automatically deleted from our server.

3. Example and first available test case: 1st LPT Challenge, two-pulse case

The first available test case of the portal is one of the datasets of the 1st LPT challenge (held in 2020, see Leclaire et al. 2021, Sciacchitano et al. 2021a), namely its two-pulse case, i.e. corresponding to PTV.

3.1. Test case description

3.1.1. Physical configuration

In order to address a flow configuration with significant turbulent structures, and large enough pressure fluctuations on the solid walls, the wake of a cylinder in ground effect is considered in that test case. Coordinate system is defined with X the streamwise, Y the spanwise and Z the wall-normal directions, respecting the right-handed rule. The cylinder has a diameter of 10 mm and its centre is located 15 mm above the wall, thus creating a gap of 10 mm. Flow numerical simulation is performed by Monotone Integrated Large Eddy Simulation, using the ONERA HPC solver FASTS. The boundary layer upstream of the cylinder is fully turbulent, with a thickness of 60 mm and a momentum thickness Reynolds number of 4,150, probed ten diameters upstream of the cylinder. The region of interest for the challenge starts 35 mm downstream of the cylinder centre, and is a parallelepipedic domain of 100 mm×50 mm×30 mm (streamwise × spanwise × wall-normal). In span, it is centred and covers half of the numerical domain; in the wall-normal direction, it starts at the lower wall. The medium considered is water, and the bulk velocity is $U_\infty = 0.667\, m.s^{-1}$. Figure 2 illustrates the turbulent structures and wall pressure fluctuations on a flow snapshot, while Figure 3 provides information on mean flow velocity. More details can be found in Leclaire et al. (2021).

3.1.2. Input data

To build the LPT and DA datasets, a cloud of virtual particles, hypothesized as fully passive tracers and initially located at random positions in space, has been propagated within the simulation, by interpolating the LES velocity field. Illumination with a limited extension in the streamwise and wall-normal directions and a set of four cameras have been defined, reproducing a typical experimental LPT setup.

Data for calibration consists of a text file containing the 3D coordinates of a set of regularly spaced points in the flow domain, together with the coordinates of their projections on the four cameras. This file, which is common to all cases of the LPT challenge, can be downloaded from each of the case pages (green button in the left panel,

Figure **4**).

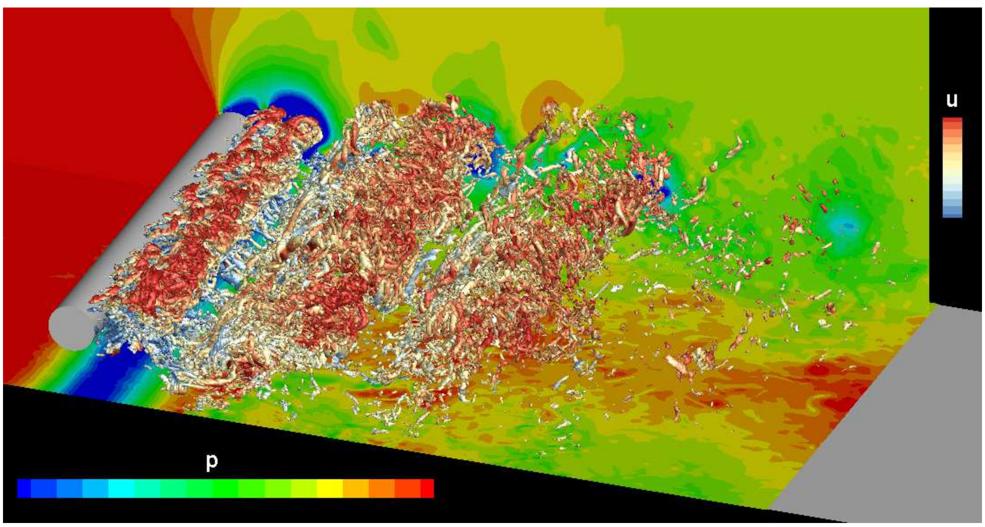


Figure 2 - Sample flow snapshot, including Q-criterion iso-surfaces color-coded by streamwise velocity u, iso-contours of pressure p at the lower and side walls.

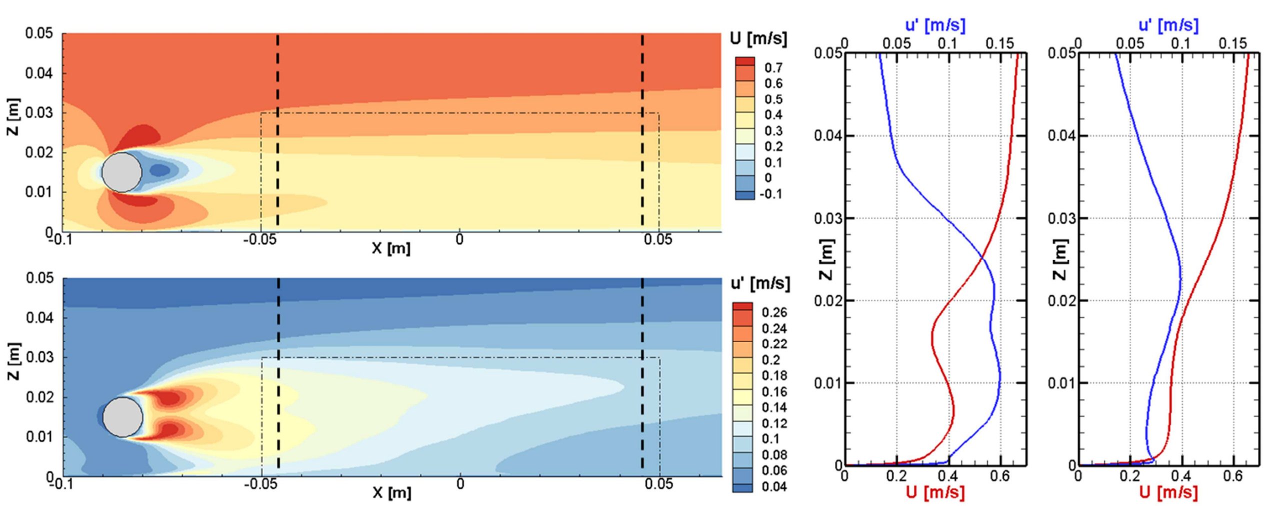


Figure 3 - Streamwise mean and fluctuating velocity components, with averaging performed in time and span. Profiles on the right correspond to streamwise locations depicted by the vertical dashed lines in the left figures.

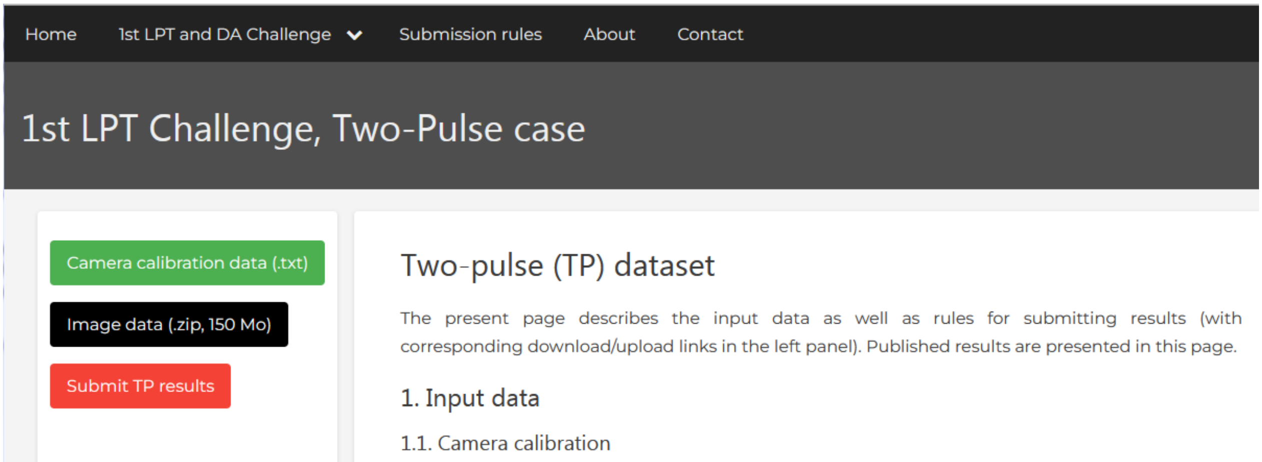


Figure 4 – Screenshot of the information page for the two-pulse case of the 1st LPT challenge

Data of the test case consist of pairs of single exposure images, with a time separation between the two laser pulses of Δt=600 µs. As the density of particles is both the main parameter of influence in the performance of LPT algorithms and one of the keys to characterizing a maximum of flow scales, six sets of image pairs were generated with image seeding densities of 0.005, 0.025, 0.05, 0.08, 0.12 and 0.16 particles per pixel (ppp). The whole set of data can be downloaded as a single zip archive by clicking on the black button on the page left panel (see Figure 4).

More complete information e.g. about the virtual camera setup and the images can be found in the webpage describing the case.

3.2. Result upload and publication

3.2.1. Requested cases and formatting rules for upload

Clicking on the "Submit TP results" button (see Figure 4) opens a form allowing to upload a file containing the results. This file should be a zip archive, with name corresponding to the short name or acronym of the algorithm used to process the results. This short name and acronym should also be indicated in one of the fields of the upload form and both should match. The zip archive should contain one result file per seeding density, each being an ASCII file. Naming conventions for these files are detailed on the portal, as well as the information they should contain and their layout. In particular, the name of each of the ASCII result files should begin with the algorithm short name.

The zip archive should mandatorily contain result files at least for seeding densities equal to 0.005, 0.025, 0.05 and 0.08 ppp (note that there is one additional mandatory seeding density compared to the actual 1st LPT Challenge, at 0.08 ppp). Any incomplete submission will be rejected. Additionally to these mandatory densities, participants are also encouraged to process other ones. In that case, all densities up to the highest one chosen should be supplied.

Additionally to uploading the file, as mentioned in section 2.3, the upload form should be filled with other information, used for result presentation in case of publication, namely: the short name (or acronym) and full name of the algorithm used for data processing and, optionally, the URL address of a publication (if any) about the algorithm, or of a webpage describing it.

3.2.2. Evaluation and publication form

Result evaluation starts when the submission form has been completed and if the archive and files contain the requested information. When evaluation is complete, an email is sent to the user, which contains a link to a form presenting the evaluation, and allowing the user to decide whether it should be published on the portal or discarded. Figure 5 contains the current version of the set of figures included in the form for the two-pulse case of the 1st LPT Challenge, with the user appearing with name 'Submission'. In this figure, it should be noted that result curves labelled 'DLR', 'ETHZ', 'INRAE-Yang' and 'LaVision' in fact correspond to performance obtained by the corresponding teams at the time of the actual LPT challenge in 2020, as described in Sciacchitano et al. (2021).

Evaluation pertains to both particle localization and velocity estimation. For both particles and velocity vectors, we then count:

- a True Positive (TP) if a ground truth particle/vector is found in the neighborhood of a detection (i.e. if the maximum componentwise distance is less than 1 voxel, the latter corresponding to a back-projected pixel and being equal to 60 μm)
- a False Negative if (FN, aka missed particle) if there is no detection in the neighborhood of a ground truth particle
- a False Positive (FP, aka ghost particle) if there is there is no ground truth particle in the neighborhood of a detection.

Precision and Recall are then derived quantities which synthetically reflect the performance of particle detection, with:

$$Precision = \frac{\#TP}{\#TP + \#FP}$$

and

$$Recall = \frac{\#TP}{\#TP + \#FN}$$

They provide the fraction of true particles among all detected particles (Precision), and the proportion of true particles retrieved (Recall).

We also compute the rms error for the particles' positions at time t0, and for the velocity vectors. The former quantity is also given as histograms for each component, and 3D plots are given to compare the distributions of estimated vs. ground truth particles in a subzone of the measurement domain, as done for the actual LPT challenge (Sciacchitano et al., 2021).

While the histograms and 3D plots are that pertaining to the submitted result only, the curves for Precision, Recall and rms errors corresponding to the submission are also compared with a selection of results present in the public database and shown in the Result page (see section 3.3). Plotting these curves together is done in the idea to to help the user grasp the performance of their result compared to the database. The four compared published results are selected as follows from the database:

- Result with highest performance in the database (if not that of the user)
- Result with lowest performance in the database (if not that of the user)
- Result with directly higher performance than that of the user
- Result with directly lower performance than that of the user

Note also that we chose to not compare the submission to all results in the database, and restricted to a maximum of 5 curves in the figures in order to maintain their readability. As performance of a measurement can be estimated according to several metrics or criteria, but a single criterion had to be chosen in order to determine a unique ranking for selecting the compared published results, we proposed a quantity which, in our view, might allow to consider and ponder the different possible metrics.

We first introduce $\overline{RMSE}_n$ as $1-\overline{RMSE}$, where $\overline{RMSE}$ is a normalized form of the rms error on velocity, defined in order to be comprised between 0 and 1. Similar to Precision and Recall (which will be evaluated for the velocity vectors in the following $Score$), $\overline{RMSE}_n$ is thus equal to 1 for maximal performance. For each of the above introduced performance quantities, here symbolically denoted by f, we then introduce the barycentric mean of f with seeding density, as

$$f^* = \frac{\sum_{ppp} f(ppp)}{\sum_{ppp} ppp}$$

where the sum is performed over all values of seeding densities uploaded by the participant. The chosen $Score$ is finally defined as

$$Score = Precision^* \times Recall^* \times \overline{RMSE}_n^{\,*} \times Risk$$

where the $Risk$ factor, defined as the sum of the density values submitted by the participant divided by the sum of the values available in the test case, ponders the risk taken by the participant in their submission.

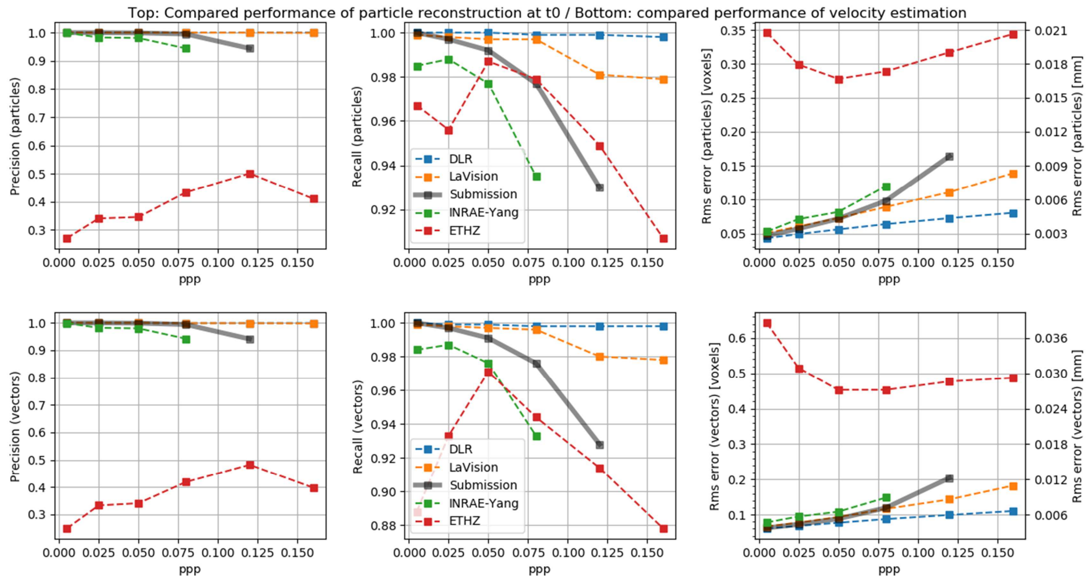
This choice has of course a degree of arbitrariness, as it does not correspond to a usual quantity in the community. For this reason, figures with only a selection of teams as in Figure 5 appear only in the decision form and are thus only visible to the user that just submitted a result, and the above defined quantity does not appear anywhere else on the portal.

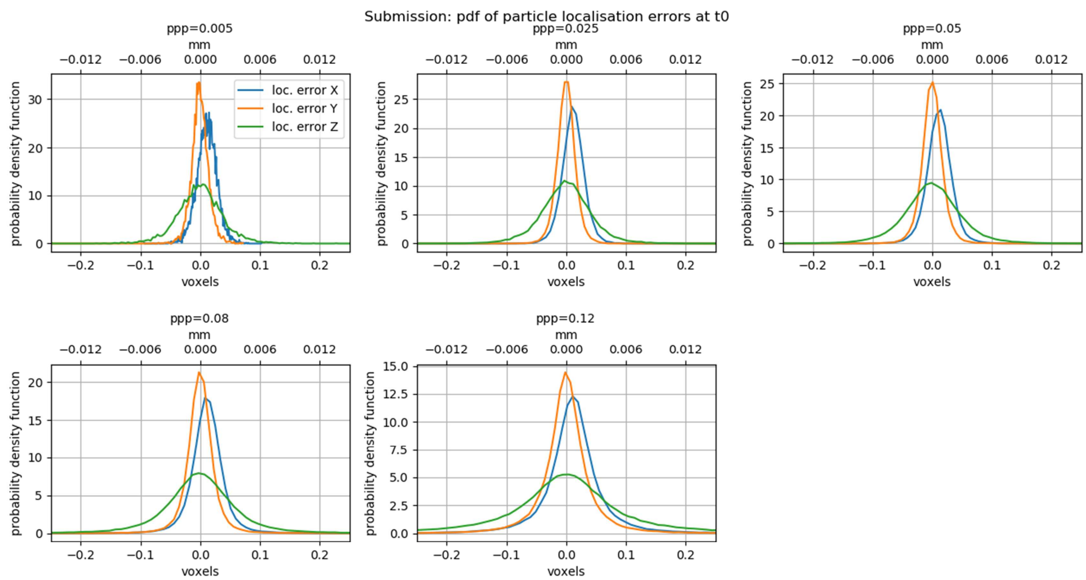
3.3. Presentation of published results

Published results for a test case are presented on a dedicated subpage, featuring tables and figures, with examples for the present test case given in Figure 6 and Figure 7. As seen in Figure 6, tables gather all quantitative data pertaining to particle detection and localization at the two time instants, as well as to the related velocity estimation. A table is given for each seeding density value of the test case. Ordering of the results in each table can be done according to any of the quantities displayed, by clicking on the corresponding column name. Clicking on a participant name in one of the table opens a subpage where all of the participants results in the table (participant's line), as well as the submission information (algorithm short and full names, URL of publication or webpage to the algorithm, and date of submission) are listed.

Below the tables, a series of figures similar to that of the top section of Figure 5 (Precision, Recall and position or velocity rms error) are produced using the data appearing in the tables. As in the case of the evaluation and publication form, curves are kept to a maximum of 5 per figure to maintain readability, so that several series of figures might appear depending on the number of published results.

In order to illustrate if a result is characterized by a preferential localization of errors (e.g. linked with edge effects, strong flow gradients, etc…), similarly to the analysis of the 1st LPT Challenge (Sciacchitano et al. 2021a), velocity error slices are extracted for each published result at the same seeding density, namely 0.08 ppp, which is the highest mandatory density to be considered. Figure 7 gives an example of such a figure, for the same participant as in Figure 5.


Top: Compared performance of particle reconstruction at t0 / Bottom: compared performance of velocity estimation
Precision (particles)
Recall (particles)
Rms error (particles) [voxels]
Rms error (particles) [mm]
Precision (vectors)
Recall (vectors)
Rms error (vectors) [voxels]
Rms error (vectors) [mm]
ppp
DLR
LaVision
Submission
INRAE-Yang
ETHZ


Submission: pdf of particle localisation errors at t0
ppp=0.005
ppp=0.025
ppp=0.05
ppp=0.08
ppp=0.12
mm
voxels
probability density function
loc. error X
loc. error Y
loc. error Z

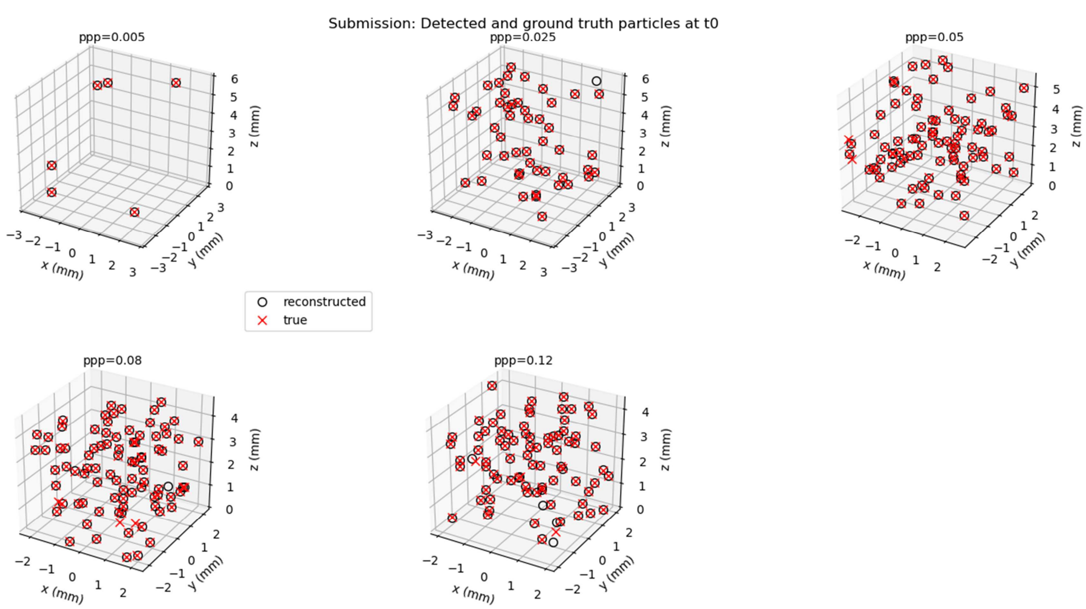

Submission: Detected and ground truth particles at t0
ppp=0.005
ppp=0.025
ppp=0.05
ppp=0.08
ppp=0.12
x (mm)
y (mm)
z (mm)
reconstructed
true

Figure 5 – Set of evaluation figures produced after result submission and appearing in the form allowing a user to decide about publishing or discarding their result. The participant is here identified by the name “Submission” and appears as a thick black line in the series of subfigures on top. Shown quantities are Precision, Recall and rms error for both particles at t0 and velocity vectors (top), histograms of positional errors for particles at t0 (middle), and 3D plots comparing true and reconstructed particles at t0 in a subzone of the domain (bottom). Note that result curves labelled 'DLR', 'ETHZ', 'INRAE-Yang' and 'LaVision' here correspond to performance obtained by the corresponding teams at the time of the actual LPT challenge in 2020, as described in Sciacchitano et al. (2021a).

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1st LPT Challenge, Two-Pulse case: Results

This page presents published results for the two-pulse case of the 1st LPT Challenge. Datasets and result upload are accessible on the left panel. Details about the test case and rules for result formatting are given in the Information page.

ppp: 0.005

Participant	Prec. t0	Recall t0	#FN t0	#TP t0	#FP t0	pos. rms error t0	X pos. rms error t0	Y pos. rms error t0	Z pos. rms error t0	Prec. t1	Recall t1	#TP t1	#FP t1	#FN t1	pos. rms error t1	X pos. rms error t1	Y pos. rms error t1	Z pos. rms error t1	Vector Prec.	Vector Recall	#TP vectors	#FP vectors	#FN vectors	vel. rms error
DLR	1	1	1	6398	0	0.0431	0.0154	0.014	0.0378	1	1	6398	0	1	0.0433	0.0155	0.0141	0.0379	1	1	6398	0	1	0.0607
ETHZ	0.271	0.967	212	6187	16660	0.346	0.129	0.109	0.302	0.273	0.976	6243	16604	156	0.279	0.126	0.092	0.232	0.249	0.888	5680	17167	719	0.643
INRAE-Yang	0.999	0.985	98	6301	7	0.0527	0.0191	0.0176	0.0459	0.999	0.984	6299	9	100	0.0574	0.0225	0.0199	0.0489	0.999	0.984	6299	9	100	0.0777
LaVision	1	0.999	5	6394	1	0.0508	0.0169	0.0158	0.0453	1	0.999	6394	1	5	0.0502	0.0166	0.0155	0.0447	1	0.999	6394	1	5	0.0662
ONERA	1	0.999	4	6395	0	0.0495	0.021	0.0168	0.0415	1	0.999	6395	0	4	0.0506	0.0217	0.0157	0.0429	1	0.999	6395	0	4	0.0675

Figure 6 – Sample table presenting the evaluation of published results, here exemplified with data from the actual 2020 1st LPT Challenge, two-pulse case (Sciacchitano et al. 2021a).

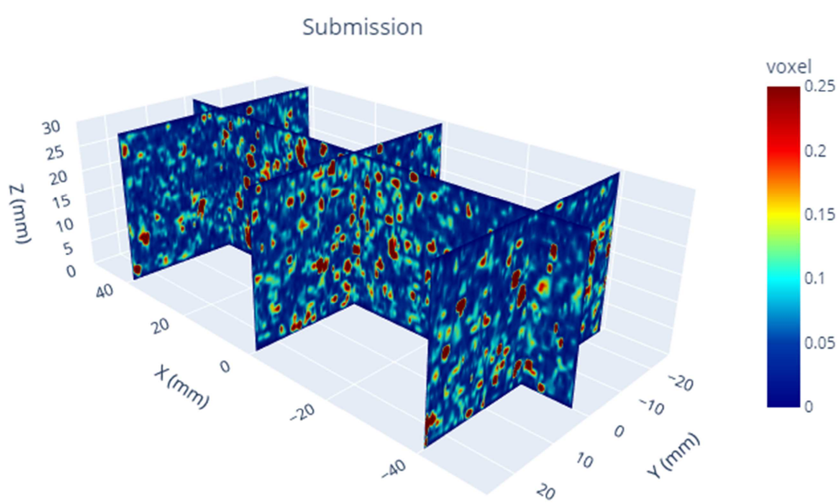

Figure 7 – Sample figure illustrating the spatial localization of velocity errors in a submitted result (norm of velocity error in voxel), corresponding to the same participant (“Submission”) as for Figure 5.

4. Next planned datasets

4.1. 1st LPT and DA Challenge

Following the first portal version opened with the two-pulse case of the 1st LPT Challenge as presented above, the next steps will consist in including the other LPT cases (four-pulse and time-resolved), as well as the DA cases, of the challenge. The portal will provide necessary information about the datasets, which can also be found in Leclaire et al. 2021, and Sciacchitano et al. (2021a, 2021b).

4.2. HOMER internal database

This first portal version has been developed within the European union HOMER project (HOlistic Metrology for aero-Elastic Research), in which the 1st LPT Challenge was also organized, and which is more directly targeted towards measurement and data assimilation for fluid-structure interaction and aeroelasticity. A database internal to the project has also been generated, considering a similar LES of a cylinder wake in ground effect, and adding periodic motion of a part of the lower wall, modelling a flexible panel driven in forced oscillation at its mid-point. Determination of the panel deformation and motion is enabled by the presence of markers with different densities, depending on the data set. Figure 8 shows an example of particle and marker distributions in a spanwise slice of one of the data set time instants. Other than the specificities incurred by the context of fluid-structure interaction (with two different panel materials, and different marker seeding densities), investigation is oriented towards situations with higher noise level in the images, and with larger effects of time truncation. A first series of processing has been done on the database, whose results will be presented as well at the Lisbon symposium (Sciacchitano et al. 2022).

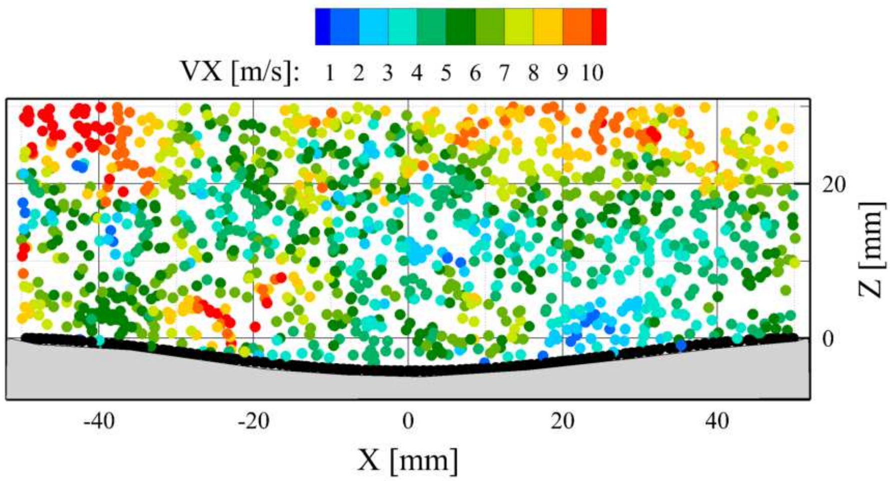

Figure 8 – Ground truth particles and markers of one of the HOMER internal datasets (**2 mm** thick slice in the **Y** direction). The moving lower wall is considered as an aluminum panel of 0.5 mm thickness, actuated with a periodic vertical forcing motion at its centre (defining the origin $(\mathbf{X}, \mathbf{Z}) = (\mathbf{0}, \mathbf{0})$). Particles are color-coded by their streamwise velocity and panel markers appear in black. From Sciacchitano et al. (2022).

4.3. Other cases and external suggestions

As we see this portal as a tool that should accompany the coming advances in optical metrology and data assimilation, it is our intention to continuously supplement it with new test cases relevant to the field. Suggestions of new datasets can also be done by getting in touch with the present authors, by sending an e-mail at the portal contact address flow-benchmarks@onera.fr. As the portal structure is now in place, with corresponding operating rules, and as conventions for result file formatting have been decided, adding new cases should amount to a more marginal cost, so that it might be quite easy to interact between teams to adapt e.g. already existing datasets to be integrated to the portal.

Acknowledgements

The authors would like to thank Andrea Sciacchitano and Andreas Schröder, as well as the members of the EU HOMER project (Holistic Optical Metrology for aero-Elastic Research), for their participation in designing and analyzing the 1st LPT Challenge dataset, with which the portal opens. This work has started within the HOMER project and has thus received funding from the European Union's Horizon 2020 research and innovation programme under grand agreement No 769237.

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